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THE DEVELOPMENT OF ALUMINUM—6 PER CENT MAGNESIUM WROUGHT ALLOYS FOR ELEVATED-TEMPERATURE SERVICE AND THEIR RESISTANCE TO CORROSION IN WATER AT TEMPERATURES UP TO 600°F

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BATTELLE MEMORIAL INSTITUTE

THE DEVELOPMENT OF ALUMINUM-6 PER CENT MAGNESIUM WROUGHT ALLOYS FOR ELEVATED-TEMPERATURE SERVICE AND THEIR RESISTANCE TO CORROSION IN WATER AT TEMPERATURES UP TO 600°F.

Contract No. W-7405-eng-92

Prepared by: K. Gruba
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July 15, 1950

TABLE OF CONTENTS

INTRODUCTION

At the present time, 2S aluminum and 72S are used in applications in which river water attains temperatures as high as about 180°F. The 2S is aluminum of commercial purity, and the 72S is a high-purity aluminum-base alloy containing 1 per cent zinc. Both of these materials are relatively weak at room temperature as well as at elevated temperatures. The objective of the present work was the development of aluminum-base alloys which had higher load-carrying capacities at all temperatures up to 600°F. without an appreciable sacrifice in resistance to corrosion by water at elevated temperatures and also without an appreciable increase in thermal neutron cross-section value. Accordingly, the work was divided into two phases. The first dealt with the development of alloys having better load-carrying capacity, and the second was concerned with the effects of temperature on the corrosion resistance of the experimental and some commercial alloys in water. The first phase is described in Section I of the report, and the second in Section II of the report.

SUMMARY

A wrought aluminum-base alloy for elevated temperature has been developed with the following composition:

6 per cent magnesium
0.5 per cent chromium
0.10 per cent titanium.

This alloy has outstanding tensile properties at all temperatures up to 600°F. Its thermal neutron cross-section value is similar to that of pure aluminum. Corrosion tests of 2000 hours' duration in refluxing, boiling, distilled water

at 212°F. indicate that its resistance to corrosion is of the same order as 2S and 72S. The resistance to corrosion of all aluminum-base alloys in water decreases rapidly with increasing water temperature, and, at 600°F., none of the aluminum-base alloys, commercial or experimental, has appreciable resistance to corrosion.

SECTION I.

THE DEVELOPMENT OF ALUMINUM-6 PER CENT MAGNESIUM WROUGHT ALLOYS FOR ELEVATED-TEMPERATURE SERVICE

The aluminum-base wrought alloys containing magnesium are not so strong at room temperature as the high-strength, heat-treatable 24S and 75S alloys of aluminum, but they have advantages of low density, excellent resistance to corrosion, moderately high tensile properties at room temperature, and very high tensile properties at elevated temperatures up to 600°F. The high tensile properties at 600°F. are indicated by the following data:

Alloy	Nominal Composition	Tensile Properties at 600°F.: Yield Strength, p.s.i.	Tensile Strength, p.s.i.	Elong. in 2 Inches, %
2S(1)	99.5%Al	1,500	2,500	90
32S-T(1)	0.9%Cu, 12.5%Si, 1.0%Mg, 0.9%Ni	3,500	6,000	60
24S-T(1)	4.5%Cu, 0.6%Mn, 1.5%Mg	6,000	7,500	65
-	6%Mg	-	10,000	90

(1) Alcoa Handbook, 1944.

The above tensile data on all the alloys were obtained after the alloys were substantially stabilized at the temperature of test.

As compared with such materials as 2S, the 6 per cent magnesium alloys not only have much higher tensile properties at room temperature to 600°F., but they have very much greater resistance to creep. However, as compared with 24S, the creep resistance of the aluminum-6% magnesium alloys is markedly inferior, as shown by the following data:

Alloy	Stress, p.s.i.	Duration, Hrs.	Initial Defor-mation, %	Final Defor-mation, %	Minimum Creep Rate, %/Hr.
24S	2,000	269	0.05	0.23	0.00016
6%Mg	2,000	4.6	0.05	4.79	Too high to measure

The general aim of the work described in this paper, then, was to obtain improved resistance to creep at 600°F., and obtain, if possible, still higher tensile properties at 600°F. but retain the good resistance to corrosio and the low density inherent in these alloys. Previous studies(2,4) have shown that small additions, particularly those having limited solid solubility sometimes have a beneficial effect upon the resistance of the alloys to creep at elevated temperature. Though some study was made of the properties of binar alloys, the principal effort was devoted to the improvement of the high-temperature properties of the aluminum-6% magnesium alloy by making small additions of one or more elements to it.

Experimental Procedures

Melting and Casting

All the melts were prepared in a clay-graphite, gas-fired crucible. A high-purity ingot containing 99.85 per cent aluminum was used except for a few heats, as noted in the accompanying tables. In these instances, 99.5 per cent aluminum was employed. The principal impurities in the aluminum ingot were iron and silicon. The alloy additions, excepting magnesium, were added in the form of aluminum-rich "hardeners". The magnesium was, of course, added in the form of commercial magnesium ingot. The melts were fluxed for 15 min.

with chlorine just prior to casting. This fluxing operation was carried out at a temperature of 1300 to 1350°F. The purpose of this fluxing operation was to provide high-quality melts relatively free of dross and gas. It is known that, if such melts contain an appreciable volume of gas, a defect known as "microporosity" is produced in alloys of the type investigated.

The melts were poured at about 1300 to 1320°F. into chill-cast slabs of the following dimensions:

1. 1 inch by 6 inches by 8 inches.
2. 1-1/4 inches by 6 inches by 10 inches.
3. 3/4 inch by 4 inches by 6 inches.

Fabrication

Usually, the surface of the ingots was quite smooth and no scalping was necessary. If, however, the surface was moderately rough, the ingot was hot rolled a relatively small amount and the resulting slab scalped to produce a sound, clean surface.

The procedure for rolling the various aluminum alloys was as follows:

1. The ingot was preheated for 16 hours near the rolling temperature.
2. The ingots were rolled at 810°F. to produce a slab 0.125 inch thick. During this operation, the metal was given five reheatings to 810°F. to 820°F.
3. The slabs were then annealed 2 hours at 650°F.
4. The annealed slabs were cold rolled to 0.060 inch thick, reannealed 2 hours at 650°F., and further cold rolled to 0.030 inch.

5. The 0.030-inch sheet was heat treated as indicated in the accompanying tables.

Heat Treatments

All the heat treatments were carried out in an automatically controlled electric furnace in which the air was circulated. During the solution heat treatment, the specimens were suspended in the furnace to avoid warpage. As indicated in the accompanying tables, most of the heat treatments included a cold-water quench from the solution heat-treating temperature. After this quenching operation, the specimens were immediately wiped dry to avoid any corrosive attack. Aging and stabilizing treatments were applied to the specimens after the solution heat treatment. In some instances, the specimens were also given a 5 per cent reduction by cold rolling as the final operation.

Tensile Tests

Test specimens were taken parallel to the direction of rolling. A standard ASTM rectangular tension-test specimen was employed for the tensile tests at room temperature as well as at 600°F. A 2-inch gauge length was employed throughout the testing program. The yield strengths of the various materials were determined at room temperature by the use of the stress-strain recording device. The yield strengths were not obtained at elevated temperatures, however, because of the special equipment required to obtain these values.

The tensile tests at room temperature were carried out at a crosshead speed of 0.03 inch per minute per inch of gauge length until the yield strength was reached. After the yield strength was reached, the rate was increased to 0.06 inch per minute per inch of gauge length. The tensile tests at 600°F. were conducted at a crosshead speed of 0.02 inch per minute per inch of gauge length until about the maximum load was reached. The speed of the movement of the crosshead was then increased to 0.06 inch per minute per inch of gauge length until the specimen failed.

A more detailed account of the furnace construction and its calibration is contained elsewhere.(2)

Creep Tests

The same ASTM rectangular standard specimens employed for the tensile tests were also employed for the creep tests. When performing the creep test, two thermocouples of 22-gauge Chromel-Alumel wire were attached to the 2-inch gauge lengths. Deformations were measured by the employment of a single platinum strip, though check tests were made by using two platinum strips, one on each side. Readings were made on the platinum strips by two observers daily. To eliminate errors in the measurement of the initial deformation - errors caused by lack of straightness of the sheet specimen - all initial deformations were corrected to the calculated amount of 0.05 inch. A detailed account of the creep test units, their calibration, and operation has been described elsewhere.(2)

Alloy Development

Tensile and creep properties were obtained on a limited number of commercial alloys for purposes of comparison with the experimental alloys. Table I contains a small amount of tensile and creep data on these commercial alloys. Alloys 2S and 72S, of course, have very poor properties at 600°F., whereas, at 600°F., 24S is known to possess the best creep resistance of any of the commercial aluminum-base wrought alloys in use today in the United States.[3] The high tensile properties of the unstabilized 24S-T3 at 600°F. are quite evident. When this composition is stabilized prior to test at 600°F., the tensile properties at room temperature and at 600°F. are very markedly reduced. Even with the stabilizing treatment of 24 hours at 650°F., the alloy is probably not completely stabilized. This is indicated by the fact that the tensile properties of the alloy in this partially stabilized condition at 600°F. are somewhat higher than those reported for this composition completely stabilized before testing at 600°F.[1] Tensile properties were also obtained on several binary alloys, including aluminum-magnesium alloys over some range in magnesium content. The purpose was to make certain that the aluminum-6 per cent magnesium base offered the greatest possibilities on which further alloy development could be based.

The data on the tensile properties and creep resistance of binary alloys are shown in Table II. Of those elements added to form binary alloys, only magnesium and manganese produce alloys which have fairly high tensile properties at 600°F. Of these two elements, 6 per cent magnesium is somewhat superior to the manganese, which can be useful in amounts of 1 or 2 per cent only. The magnesium alloys, of course, also have markedly better tensile properties at room temperature.

TABLE I. TENSILE AND CREEP PROPERTIES OF A FEW COMMERCIAL ALLOYS IN FORM OF 0.030-INCH ALUMINUM SHEET

Heat No.	Intended Composition, Bal. Aluminum (Mg,% / Others,%)	Heat* Treatment	Test Temp., °F.	Tensile Properties: Elong., % in 2 Inches	Tensile Properties: Yield Strength, 0.2% Offset, p.s.i.	Tensile Properties: Tensile Strength, p.s.i.	Creep Properties: Stress, p.s.i.	Creep Properties: Duration, Hrs.	Creep Properties: Initial Deformation, %	Creep Properties: Final Total Deformation, %	Creep Properties: Minimum Creep Rate, %/Hr.	Creep Properties: Total Deformation in 250 Hrs., %
A5582	2S	HTS-16	Room	35.8	5,400	12,500						
		HTS-16	600	66.0		2,850	2,000	Creep rate at 600°F. very high				
A5582	2S	S	Room	35.8	4,700	12,400						
A5850	2S	S	Room	44.0	3,600	9,630						
		S	600	77.5		2,250	2,000	" "	" "	" "		
A6137	2S	HTS-1	Room	28.3	5,025	12,775						
		HTS-1	600	56.0		2,500	2,000	" "	" "	" "		
A5583	72S	HTS-16	Room	33.7	6,000	12,300						
		HTS-16	600	47.0		2,885	2,000	" "	" "	" "		
A6138	72S	HTS-1	Room	25.5	4,950	12,250						
		HTS-1	600	58.0		2,150	2,000	" "	" "	" "		
Commercial Product	24S	T3	Room	17.5	53,600	69,100						
		T3	600	12.0		20,000	2,000	499.0	0.05	0.225	0.00022	0.176
		T3	600				2,000	501.7	0.05	0.233	0.00022	0.156
Commercial Product	24S	X	Room	16.0	14,350	37,400						
		X	600	37.0		9,225	2,000	269.1	0.05	0.229	0.00016	0.224

* Heat Treatment:

- HT - Solution heat treated at 810-820°F. for the time indicated by the number attached and quenched in cold water. An "S" following the HT indicates that the alloy has also been stabilized at 650°F. for 24 hours.
- T3 - Commercial designation indicating the material to be solution heat treated at 920°F. and then cold straightened by the producer.
- X - Material received in the T3 condition, then stabilized 24 hours at 650°F. prior to testing.
- S - Indicates the alloy was stabilized only at 650°F. for 24 hours.

TABLE XI. TENSILE AND CREEP PROPERTIES OF ALUMINUM-BASE BINARY ALLOYS IN FORM OF 0.030-INCH SHEET

	Intended Composition, Bal. Aluminum				Tensile Properties			Creep Properties					
Heat No.	Mg,%	Others,%	Heat* Treatment	Test Temp., °F.	Elong., % in 2 Inches	Yield Strength, 0.2% Offset, p.s.i.	Tensile Strength, p.s.i.	Stress, p.s.i.	Duration, Hrs.	Initial Deforma- tion, %	Final Total Deforma- tion, %	Min. Creep Rate, %/Hr.	Total De- formation in 250 Hrs., %
A5584	6.0		HTS-16	Room	28.7	17,850	40,000						
			HTS-16	600	93.5		10,150	1,000	53.0	0.05	4.746	0.09	-
			HTS	600				1,300	35.0	0.05	10.4	0.275	-
A5584	6.0		S	Room	27.7	18,725	41,050						
			S	600				500	47.6	0.046	1.25	0.024	-
A5985	6.0		HTS-1	Room	26.0	17,000	38,875						
				600	111.3		9,425	2,000	4.6	0.05	4.791	(1)	-
A5985	6.0		HTAS-1	Room	26.5	16,725	38,050						
A5935		1.6Be	HTS-1	Room	39.0	5,300	14,200						
			HTS-1	600	81.5		2,800						
A5935		1.6Be	S	Room	35.8	5,700	14,000						
			S	600	76.5		2,800						
A5859		2.0Bi	S	Room	49.2	3,450	9,475						
			S	600	75.0		1,925						
A5852		6.0Cd	S	Room	49.7	4,350	10,200						
			S	600	58.7		2,050						
A5861		0.5Cr	S	Room	21.5	9,450	13,250						
			S	600	14.5		4,800						
A5863		4.0Cu	HTS**	Room	26.0	8,515	24,700						
			HTS	600	53.5		4,300						
A5864		2.0Fe	S	Room	39.7	6,375	15,000						
			S	600	43.0		4,000						
A5862		2.0Mn	S	Room	16.5	20,550	22,675						
			S	600	26.5		8,000						
A5858		2.0Ni	S	Room	32.0	5,700	16,300						
			S	600	70.5		2,900						
A5855		2.0Pb	S	Room	51.5	3,200	9,775						
			S	600	68.0		2,150						

TABLE II. (CONTINUED)

Heat No.	Intended Composition, Bal. Aluminum Mg, %	Intended Composition, Bal. Aluminum Others, %	Heat* Treatment	Test Temp., °F.	Tensile Properties Elong., % in 2 Inches	Tensile Properties Yield Strength, 0.2% Offset, p.s.i.	Tensile Properties Tensile Strength, p.s.i.	Creep Properties Stress, p.s.i.	Creep Properties Duration, Hrs.	Creep Properties Initial Deformation, %	Creep Properties Final Total Deformation, %	Creep Properties Min. Creep Rate, %/Hr.	Creep Properties Total Deformation in 250 Hrs., %
A5856		2.0Sb	S	Room	43.2	4,100	11,800						
			S	600	68.5		2,250						
A5853		2.0Si	S	Room	39.0	5,875	15,200						
			S	600	62.5		2,900						
A5854		2.0Sn	S	Room	48.5	4,000	9,850						
			S	600	55.5		1,900						
A5860		0.5Ti	S	Room	37.5	5,650	11,950						
			S	600	43.0		3,400						
A5851		6.0Zn	S	Room	30.7	4,350	12,800						
			S	600	87.5		2,000						

* Heat Treatment:

HT - Solution heat treated at 810-820°F. for the time indicated and quenched in cold water. An "S" following the HT indicates that the alloy has also been stabilized at 650°F. for 24 hours. An "A" indicates the alloy was aged 16 hours at 350°F. The order of these symbols indicates the order in which the treatments were carried out.

S - Indicates the alloy was stabilized only at 650°F. for 24 hours.

** HTS - Solution heat treated at 960°F. for 20 minutes, quenched in cold water, and then stabilized 24 hours at 650°F.

(1) No time-deformation curve available.

The data on the 6 per cent magnesium binary alloy also show the effect of heat treating this composition. As would be expected, the various heat treatments have no appreciable effect upon the tensile properties of the wrought alloy at room temperature or at 600°F. The reason is that, in the as-hot-rolled condition, all of the magnesium is in solid solution. Consequently, a subsequent heat treatment has no appreciable effect upon the structure or properties obtained. As indicated previously, the resistance to creep of such 6 per cent magnesium binary alloys is rather poor as compared with that of the 24S composition.

In view of the good tensile properties of the 6 per cent magnesium binary alloy, its low density, and high resistance to corrosion in normal exposures, it was selected as a base for further development. This further development was carried out by making additions to this base, the purpose of which was mainly to improve the resistance to creep at 600°F. Accordingly, a considerable number of single additions were made to this binary base. The effects produced on the creep resistance are quite remarkable, as shown by the data in Table III. As noted previously, when the binary alloy at 600°F. is subject to a 2000 p.s.i. load, the rate of creep is too rapid to measure successfully. When chromium is added, very substantial reductions in creep rate were obtained. Fair resistance to creep is also obtained by reducing the magnesium and adding approximately 4.5 per cent copper, approaching the 24S composition. However, 1 to 3 per cent copper in a 5 per cent magnesium base is without appreciable benefit. Manganese, vanadium, and possibly zirconium also appear to have some beneficial effect upon the creep resistance of the 6 per cent magnesium alloys. Of these additions, however, chromium appeared to be the most beneficial, and considerable effort was made

TABLE III. TENSILE AND CREEP PROPERTIES OF TERNARY ALLOYS OF ALUMINUM CONTAINING MAGNESIUM - TESTED IN FORM OF 0.030-INCH SHEET

Heat No.	Intended Composition, Bal. Aluminum		Heat* Treatment	Test Temp., °F.	Tensile Properties			Creep Properties					
	Mg, %	Others, %			Elong., % in 2 Inches	Yield Strength, 0.2% Offset, p.s.i.	Tensile Strength, p.s.i.	Stress, p.s.i.	Duration, Hrs.	Initial Deformation, %	Final Total Deformation,%	Min. Creep Rate, %/Hr.	Total Deformation in 250 Hrs.,%
A5597	6.0	0.01Be	HTS-16 HTS-16	Room 600	28.3 (1)	18,000	41,000 10,000						
A5932	6.0	0.16Be	HTS-1 HTS-1	Room 600	29.0 117.0	19,300	43,000 9,500						
A5932	6.0	0.16Be	HTS-16 HTS-16	Room 600	27.2 (1)	18,200	41,000 9,350	2,000	6.0	0.05	7.814	1.0	-
A5934	6.0	1.6Be	HTS-1	Room	23.7	21,750	47,250						
A5934	6.0	1.6Be	HTS-16	Room 600	26.2 111.2	21,225	45,400 9,675	2,000	17.4	0.05	7.321	(2)	
A5591	6.0	0.15Cr	HTS-16 HTS-16	Room 600	27.5 105.5	22,400	44,375 9,200						
A5591	6.0	0.15Cr	S S	Room 600	27.3 95.0	22,750	44,800 9,575						
A5592	6.0	0.35Cr	HTS-16 HTS-16	Room 600	26.0 84.0	24,400	47,500 10,700	2,000	263.0	0.028	2.592	0.008	2.472
A5593	6.0	0.50Cr	HTS-16 HTS-16	Room 600	24.0 80.0(3)	24,550	46,700 10,775(3)	2,000	119.6	0.05	3.02	0.0137	-
A5931	6.0	0.35Cr	HTS-1 HTS-16 HTS-16	Room Room 600	27.2 25.0 95.0	23,950 23,550	45,625 46,250 9,525	2,000	23.7	0.05	3.34	0.080	
A5977	6.0	0.50Cr	HTS-1	Room 600	22.5 71.5	26,050	48,250 9,575	2,000	98.9	0.05	13.92	0.089	
A5977	6.0	0.50Cr	HTAS-1 HTAS-1	Room 600	23.0	25,675	47,275	2,000	18.9	0.05	6.67	0.350	
A6136	6.0	0.50Cr	HTS-1 HTS-1	Room 600	23.0 63.0	25,200	47,000 10,950	2,000	169.8	0.05	1.98	0.0007	
A5873	1.5	4.5Cu	HTS(4) HTS(4)	Room 600	16.3 36.0	12,325	32,600 8,500	2,000	167.2	0.05	1.44	0.0042	

TABLE III. (CONTINUED)

Heat No.	Intended Composition, Bal. Aluminum: Mg, %	Intended Composition, Bal. Aluminum: Others, %	Heat* Treatment	Test Temp., °F.	Tensile Properties: Elong., % in 2 Inches	Tensile Properties: Yield Strength, 0.2% Offset, p.s.i.	Tensile Properties: Tensile Strength, p.s.i.	Creep Properties: Stress, p.s.i.	Creep Properties: Duration, Hrs.	Creep Properties: Initial Deformation, %	Creep Properties: Final Total Deformation, %	Creep Properties: Min. Creep Rate, %/Hr.	Creep Properties: Total Deformation in 250 Hrs., %
A5874	3.5	2.5Cu	S	Room	18.7	14,100	31,500						
			S	600	116.0		8,000	2,000	2.8	0.05	5.03	(2)	
A5875	5.0	1.0Cu	S	Room	21.7	18,050	39,850						
			S	600	(1)		9,600	2,000	3.3	0.05	3.28	(2)	
A5983	5.0	3.0Cu	HTS-1	Room	18.7	17,500	39,400						
			HTS-1	600	105.0		9,325	2,000	16.2	0.05	(2)	(2)	
A5983	5.0	3.0Cu	HTAS-1	Room	18.0	15,750	38,350						
A5927	6.0	0.5Mn	HTS-1	Room	26.5	24,550	48,300						
			HTS-1	600	109.5		9,450						
A5927	6.0	0.5Mn	HTS-16	Room	26.0	22,925	45,850						
			HTS-16	600	123.0		9,050	2,000	17.2	0.05	10.56	0.460	
A5930	3.0	3.0Si	HTS-1	Room	31.5	6,800	16,900						
A5930	3.0	3.0Si	HTS-16	Room	31.0	6,725	16,500						
			HTS-16	600	76.0		2,750						
A5594	6.0	0.05Ti	HTS-16	Room	29.8	17,500	39,850						
			HTS-16	600	116.0		9,600						
A5594	6.0	0.05Ti	S	Room	28.5	18,700	41,150						
			S	600	124.5		10,500						
A5595	6.0	0.10Ti	HTS-16	Room	27.8	17,800	39,850						
			HTS-16	600	110.5		9,500						
A5595	6.0	0.10Ti	S	Room	28.7	19,650	41,500						
			S	600	105.0(3)		9,650(3)						
A5596	6.0	0.25Ti	HTS-16	Room	26.0	19,500	41,200						
			HTS-16	600	121.0		9,800	2,000	2.7	0.05	3.60	1.20	
A6022	6.0	0.25Ti	HTS-1	Room	25.0	19,900	42,200						
			HTS-1	600	113.3		9,950	2,000	6.3	0.05	3.39	(2)	-
A6022	6.0	0.25Ti	HT-1	Room	12.7	37,225	46,500						
			HT-1	600	101.3		7,750	2,000	3.6	(2)	(2)	(2)	-

TABLE III. (CONTINUED)

Heat No.	Intended Composition, Bal. Aluminum: Mg, %	Intended Composition, Bal. Aluminum: Others, %	Heat* Treatment	Test Temp., °F.	Tensile Properties: Elong., % in 2 Inches	Tensile Properties: Yield Strength, 0.2% Offset, p.s.i.	Tensile Properties: Tensile Strength, p.s.i.	Creep Properties: Stress, p.s.i.	Creep Properties: Duration, Hrs.	Creep Properties: Initial Deforma-tion, %	Creep Properties: Final Total Deforma-tion, %	Creep Properties: Min. Creep Rate, %/Hr.	Creep Properties: Total De-formation in 250 Hrs., %
A5588	6.0	0.10V	HTS-16	Room	27.0	18,875	40,925						
			HTS-16	600	118.0		8,975						
A5590	6.0	0.50V	HTS-16	Room	25.3	19,100	41,700						
			HTS-16	600	97.0		9,400	2,000	2.7	0.05	3.86	1.25	-
A5585	6.0	0.10Zr	HTS-16	Room	26.5	17,650	39,850						
			HTS-16	600	117.5		8,850						
A5585	6.0	0.10Zr	S	Room	28.0	17,900	40,950						
			S	600	107.5		9,150						
A5586	6.0	0.25Zr	HTS-16	Room	27.5	17,575	39,200						
			HTS-16	600	114.0		9,675						
A5586	6.0	0.25Zr	S	Room	28.0	18,700	41,600						
			S	600	132.5(3)		9,325(3)						
A5587	6.0	0.50Zr	HTS-16	Room	17.2	16,475	37,900						
			HTS-16	600	132.5		9,250	2,000	4.5	0.05	5.5	1.35	-
A5587	6.0	0.50Zr	S	Room	28.0	18,650	41,400						
			S	600	120.0		9,000						

* Heat Treatment:

HT - Solution heat treated at 810-820°F. for the time indicated by the number attached and quenched in cold water. An "S" following the HT indicates that the alloy has also been stabilized at 650°F. for 24 hours.
An "A" indicates the alloy was aged 16 hours at 350°F.
The order of the symbols indicates the order in which the treatments were carried out.

S - Stabilized only at 650°F. for 24 hours.

(1) Specimen did not rupture.
(2) No time-deformation curve available.
(3) One test value.
(4) Solution heat treated at 925°F. for 20 minutes, quenched in cold water, and stabilized 24 hours at 650°F.

to make further additions to the 6 per cent magnesium-0.5 per cent chromium base to still further improve its creep resistance.

The tensile properties and creep data on a considerable number of the more complex alloys, most of which contain 6 per cent magnesium, are listed in Table IV. Of these additions to the aluminum-6 per cent magnesium base, chromium and titanium appear to be the most beneficial. As a result of this work, the following alloy appeared to have an excellent combination of tensile properties and creep resistance at 600°F.:

6 per cent magnesium
0.5 per cent chromium
0.10 per cent titanium

Although an alloy of this type without the chromium and titanium has a creep rate at 600°F.-2000 p.s.i. load which is too rapid to be measured, the alloy with these additions had a minimum creep rate of only 0.003 to 0.0004 per cent per hour.

The high-temperature tensile properties of alloys cold rolled 5 per cent are somewhat inferior to those of the same material not given such a cold-rolled treatment. Creep data on alloys cold rolled 5 per cent were not obtained. In all probability, however, such a treatment would have an adverse effect upon the creep resistance because of the recrystallization which may occur during the course of the test.

Figure 1 shows a comparison of the tensile properties of the following five alloys at room temperature:

1. 24S-T3 (solution heat treated and cold straightened by the producer).
2. 24S-T3 stabilized 24 hours at 650°F.
3. Aluminum-6 per cent magnesium binary - heat treated and stabilized.
4. Experimental alloy, containing 6%Mg, 0.5%Cr, 0.1%Ti - heat treated and stabilized.
5. Same (duplicate heat).

TABLE IV. TENSILE AND CREEP PROPERTIES OF COMPLEX ALUMINUM-BASE ALLOYS CONTAINING MAGNESIUM

(Tested in the Form of 0.030-Inch Sheet)

Heat No.	Intended Composition, Bal. Aluminum: Mg, %	Intended Composition, Bal. Aluminum: Others, %	Heat* Treatment	Test Temp., °F.	Tensile Properties: Elong., % in 2 Inches	Tensile Properties: Yield Strength, 0.2% Offset, p.s.i.	Tensile Properties: Tensile Strength, p.s.i.	Creep Properties: Stress, p.s.i.	Creep Properties: Duration, Hrs.	Creep Properties: Initial Deformation, %	Creep Properties: Final Total Deformation, %	Creep Properties: Minimum Creep Rate, %/Hr.	Creep Properties: Total Deformation in 250 Hrs., %
A5928	6.0	0.50Mn 0.16Be	HTS-1 HTS-1	Room 600	26.2 117.0(1)	24,225	47,500 8,650						
A5928	6.0	0.50Mn 0.16Be	HTS-16 HTS-16	Room 600	22.2 102.0	22,750	47,300 9,300	2,000	19.4	0.050	2.55	(2)	-
A5929	5.0	1.00Cu 0.16Be	HTS-1 HTS-1	Room 600	24.0 117.0(1)	18,600	41,750 9,750						
A5929	5.0	1.00Cu 0.16Be	HTS-16 HTS-16	Room 600	24.0 106.5(1)	18,425	41,000 9,725						
A5933	6.0	0.16Be 0.35Cr	HTS-1	Room	26.7	24,350	46,050						
A5933	6.0	0.16Be 0.35Cr	HTS-16 HTS-16	Room 600	24.5 119.5	25,000	48,275 9,050						
A5978	6.0	0.50Cr 0.75Mn	HTS-1 HTS-1	Room 600	19.2 73.5	28,375	53,650 11,000	2,000	18.4	0.05	2.52	(2)	-
A5978	6.0	0.50Cr 0.75Mn	HTAS-1 HTAS-1	Room 600	19.0	27,625	50,625	2,000	47.9	0.05	4.35	0.0775	-
A5979	4.0	0.50Cr 2.00Cu	HTS-1 HTS-1	Room 600	17.0 71.0	20,000	39,450 9,975	2,000	91.7	0.05	2.07	1.95	-
A5979	4.0	0.50Cr 2.00Cu	HTAS-1 HTAS-1	Room 600	15.0	19,900	42,275	2,000	288.2	0.05	1.47	0.0045	1.35
A5981	6.0	0.50Cr 0.25Mo	HTS-1 HTS-1	Room 600	23.5 72.0	24,825	46,425 9,775						
A5981	6.0	0.50Cr 0.25Mo	HTAS-1	Room	23.0	24,100	44,925						
A5984	5.0	3.00Cu 0.25Mn	HTS-1 HTS-1	Room 600	16.5 88.3	20,725	40,625 8,450	2,000	1.0	(2)	(2)	(2)	-
A5984	5.0	3.00Cu 0.25Mn	HTAS-1	Room	19.0	19,675	39,600						

TABLE IV. (CONTINUED)

Heat No.	Intended Composition, Bal. Aluminum: Mg, %	Intended Composition, Bal. Aluminum: Others, %	Heat* Treatment	Test Temp., °F.	Tensile Properties: Elong., % in 2 Inches	Tensile Properties: Yield Strength, 0.2% Offset, p.s.i.	Tensile Properties: Tensile Strength, p.s.i.	Creep Properties: Stress, p.s.i.	Creep Properties: Duration, Hrs.	Creep Properties: Initial Deformation, %	Creep Properties: Final Total Deformation, %	Creep Properties: Minimum Creep Rate, %/Hr.	Creep Properties: Total Deformation in 250 Hrs., %
A6024	6.0	0.25Ti	HTS-1	Room	21.0	24,000	47,275						
		0.25Mn	HTS-1	600	83.5		10,550	2,000	24.3	0.05	3.27	(2)	-
A6024	6.0	0.25Ti	HTCR-1	Room	12.0	42,425	51,575						
		0.25Mn	HTCR-1	600	92.0		8,200						
A5980	6.0	0.50Cr	HTS-1	Room	22.5	27,200	49,775						
		0.10Ti	HTS-1	600	63.0		11,200	2,000	289.0	0.050	0.117	0.00034	0.111
			HTS-1	600				2,000	358.1	0.05	0.182	0.0002	0.110
A5980	6.0	0.50Cr 0.10Ti	HTAS-1	Room	24.0	27,425	49,050						
A5980	6.0	0.50Cr	HTCR-1	Room	15.5	40,425	52,450						
		0.10Ti		600	60.5		9,100						
A5980	6.0	0.50Cr	HTSCR-1	Room	15.7	39,900	52,400						
		0.10Ti		600	60.5		9,900						
A6023	6.0	0.50Cr	HTS-1	Room	21.2	22,950	43,450						
		0.25Ti	HTS-1	600	64.0		9,375	2,000	336.8	0.049	5.54	1.17	4.72
A6023	6.0	0.50Cr	HTCR-1	Room	10.5	39,850	47,900						
		0.25Ti	HTCR-1	600	57.5		8,575						
A6120	6.0	0.50Cr	HTS-1	Room	24.5	27,250	50,100						
		0.05Ti	HTS-1	600	61.0		11,350	2,000	479.9	0.050		0.0001	
			HTS-1	600				2,000	339.5	0.050(3)	0.106(3)	0.00005(4)	0.100
A6120	6.0	0.50Cr	HTCR-1	Room	14.5	42,750	53,550						
		0.05Ti	HTCR-1	600	59.5		10,625						
A6120	6.0	0.50Cr	HTSCR-1	Room	14.0(1)	41,900(1)	53,200(1)						
		0.05Ti	HTSCR-1	600	66.0		10,625						
A6121	6.0	0.50Cr	HTS-1	Room	22.2	26,150	47,900						
		0.10Ti	HTS-1	600	54.5		11,375	2,000	292.0	0.050	0.666	0.0007(5)	0.630
A6122	6.0	0.50Cr	HTS-1	Room	22.2	25.650	46,600						
		0.15Ti	HTS-1	600	55.5		11,525	2,000	307.6	0.05	0.213	0.00023	0.182
A6123	6.0	0.50Cr	HTS-1	Room	20.7	26,175	46,700						
		0.25Ti	HTS-1	600	58.0		10,575						

TABLE IV. (CONTINUED)

Heat No.	Intended Composition, Bal. Aluminum: Mg, %	Intended Composition, Bal. Aluminum: Others, %	Heat* Treatment	Test Temp., °F.	Tensile Properties: Elong., % in 2 Inches	Tensile Properties: Yield Strength, 0.2% Offset, p.s.i.	Tensile Properties: Tensile Strength, p.s.i.	Creep Properties: Stress, p.s.i.	Creep Properties: Duration Hrs.	Creep Properties: Initial Deformation, %	Creep Properties: Final Total Deformation, %	Creep Properties: Minimum Creep Rate, %/Hr.	Creep Properties: Total Deformation in 250 Hrs., %
A 6124(6)	6.0	0.50Cr	HTS-1	Room	21.2	25,900	47,250						
		0.05Ti	HTS-1	600	63.5		10,100	2,000	168.2	0.050	2.58	0.0085	-
			HTS-1	600				2,000	52.4	0.050	1.826	(2)	-
A6125(6)	6.0	0.50Cr	HTS-1	Room	20.0	26,825	48,200						
		0.10Ti	HTS-1	600	64.0		10,500	2,000	295.8	0.050	0.277	0.00045	0.253
A6126(6)	6.0	0.50Cr	HTS-1	Room	21.7	27,650	47,500						
		0.15Ti	HTS-1	600	56.0		10,625	2,000	339.2	0.05	1.61	0.0029	1.38
A6127(6)	6.0	0.50Cr	HTS-1	Room	19.0	29,525	49,825						
		0.25Ti	HTS-1	600	52.0		10,175	2,000	172.2	0.050	0.182	0.00043	-
A5982	6.0	1.50Cu	HTS-1	Room	18.5	29,525	54,125						
		0.75Mn	HTS-1	600	98.5		10,000	2,000	3.2	0.050	2.80	(2)	-
		0.25Zr	HTAS-1	Room	18.0	29,250	52,975						
A5876	1.5	4.50Cu											
		0.60Mn	HTS(7)	Room	14.7	14,400	34,550						
		0.40Si	HTS(7)	600	45.5		8,575	2,000	92.9	0.050	0.457	0.003	-
		0.35Fe											
A5877	1.5	4.40Cu											
		0.80Mn	HTS(7)	Room	14.7	12,775	32,700						
		0.25Fe	HTS(7)	600	32.0		9,950						
		0.15Si											
A6021	1.20	2.00Cu	HTA(8)	Room	13.2	49,675	63,050						
		0.70Si	HTA(8)	600	16.7		11,700	2,000	99.9	0.050	2.421	1.22	-
		0.25Cr	HTAS(8)	Room	16.0		27,500						
			HTAS(8)	600	38.0		6,375	2,000	137.5	0.050	3.99	1.95	-

* Heat Treatments:

HT - Solution heat treated at 810-820°F. for the time indicated by the number attached and quenched in cold water. An "S" following the HT indicates the alloy has also been stabilized at 650°F. for 24 hours. An "A" indicates the alloy was aged 16 hours at 350°F. A "CR" indicates the alloy was also reduced 5% by cold rolling. The order of the symbols indicates the order in which the treatments were carried out.

(1) One test value.
(2) No time-deformation curve available.
(3) This specimen had two extensometers attached; values are the average of the two gauges.
(4) The creep rate is between 0.00001 and 0.0001 per cent per hr.
(5) This rate was between 50 and 100 hours. The rate increased to 0.0015 per cent per hour for the remainder of the test.
(6) Prepared from commercial-grade aluminum.
(7) Solution heat treated at 925°F. for 20 minutes, quenched in cold water, and then stabilized at 650°F. for 24 hours.
(8) Solution heat treated at 960°F. for 1/2 hour, quenched in cold water, and aged at 320°F. for 18 hours. An "S" indicates the alloy had also been stabilized at 650°F. for 24 hours.

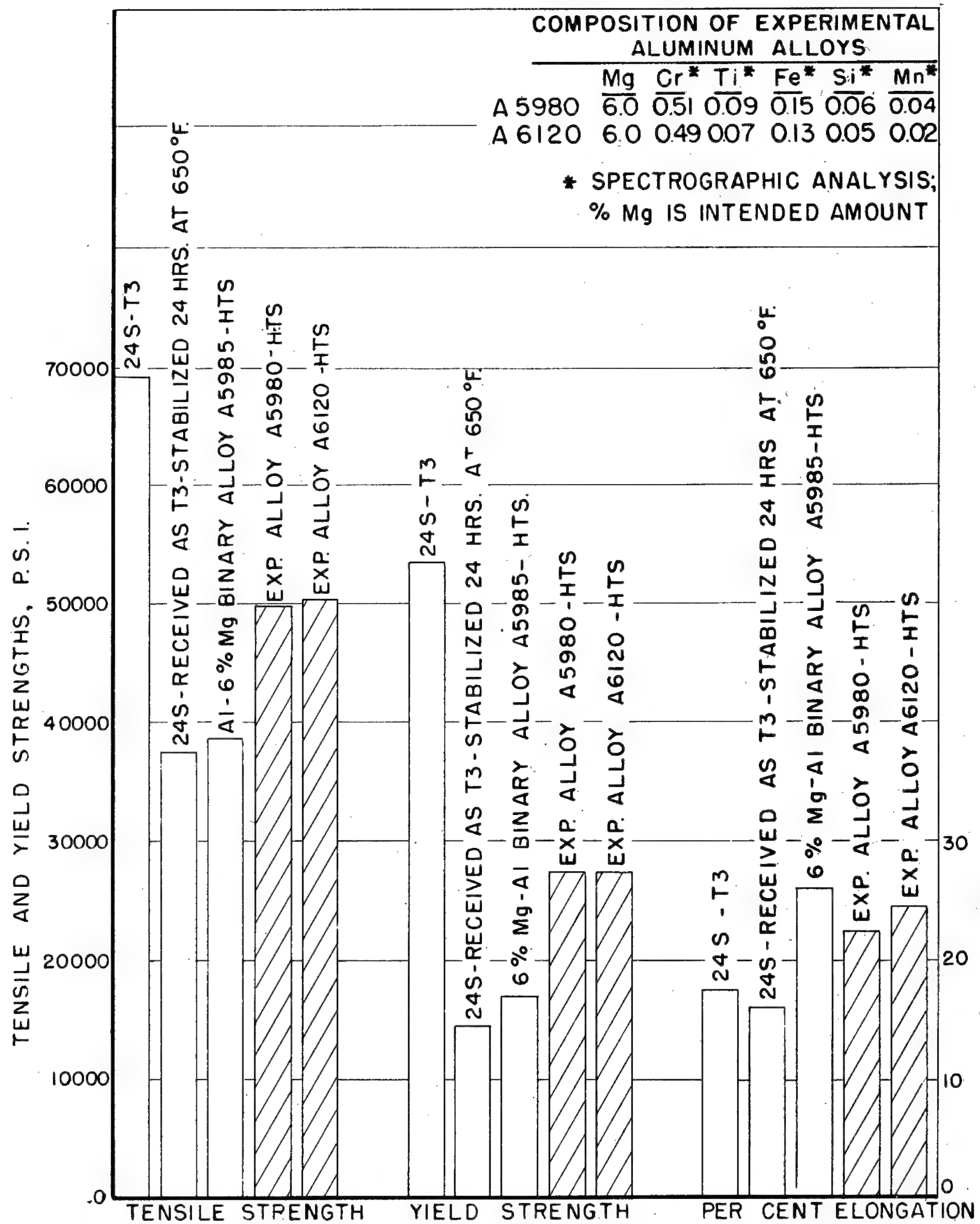

FIGURE 1. COMPARISON OF THE TENSILE PROPERTIES OF 24S, 6% Mg-Al BINARY AND EXPERIMENTAL ALLOYS AT ROOM TEMPERATURE, MATERIAL TESTED IN FORM OF 0.030-INCH ROLLED SHEET

0-16199

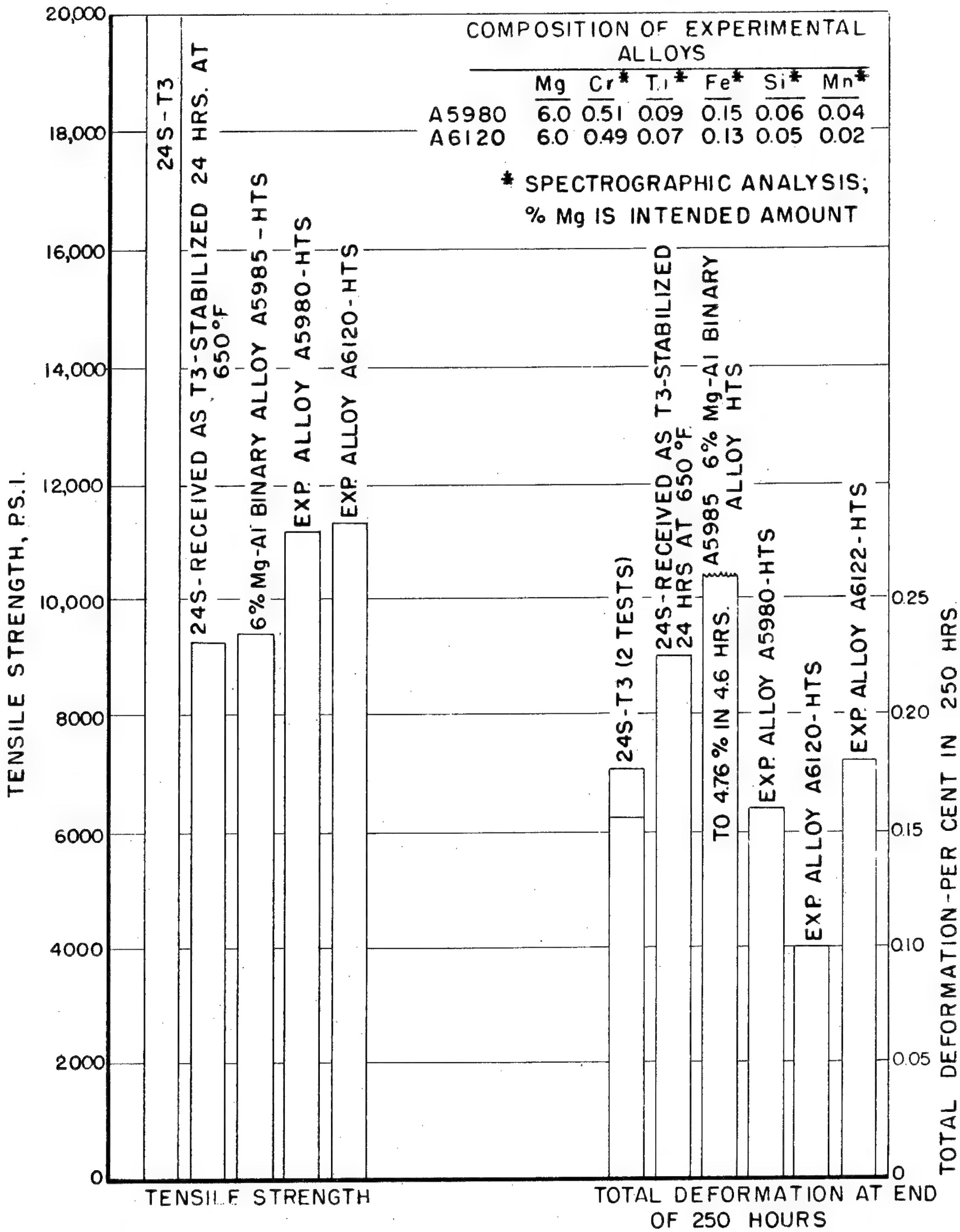

FIGURE 2. COMPARISON OF THE TENSILE AND CREEP PROPERTIES OF 24S, 6% Mg-Al BINARY AND EXPERIMENTAL ALLOYS AT 600 °F MATERIAL TESTED IN FORM OF 0.030-INCH SHEET.

0-16200

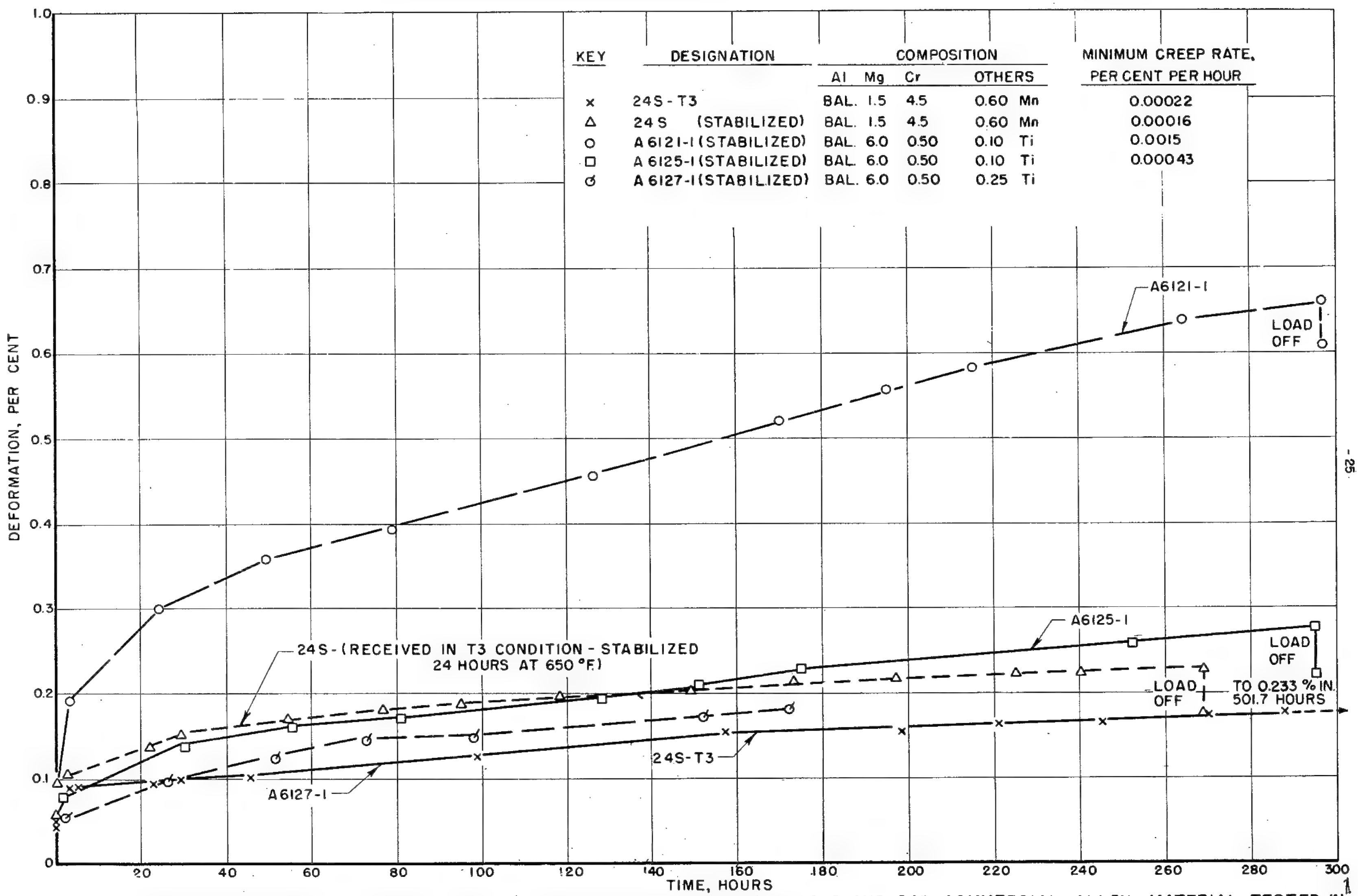

FIGURE 3. TIME-DEFORMATION CURVES OF THREE EXPERIMENTAL ALUMINUM ALLOYS AND 24S COMMERCIAL ALLOY. MATERIAL TESTED IN FORM OF 0.030-INCH ROLLED SHEET AT 600°F.-2000 P.S.I. LOAD.

0-16201

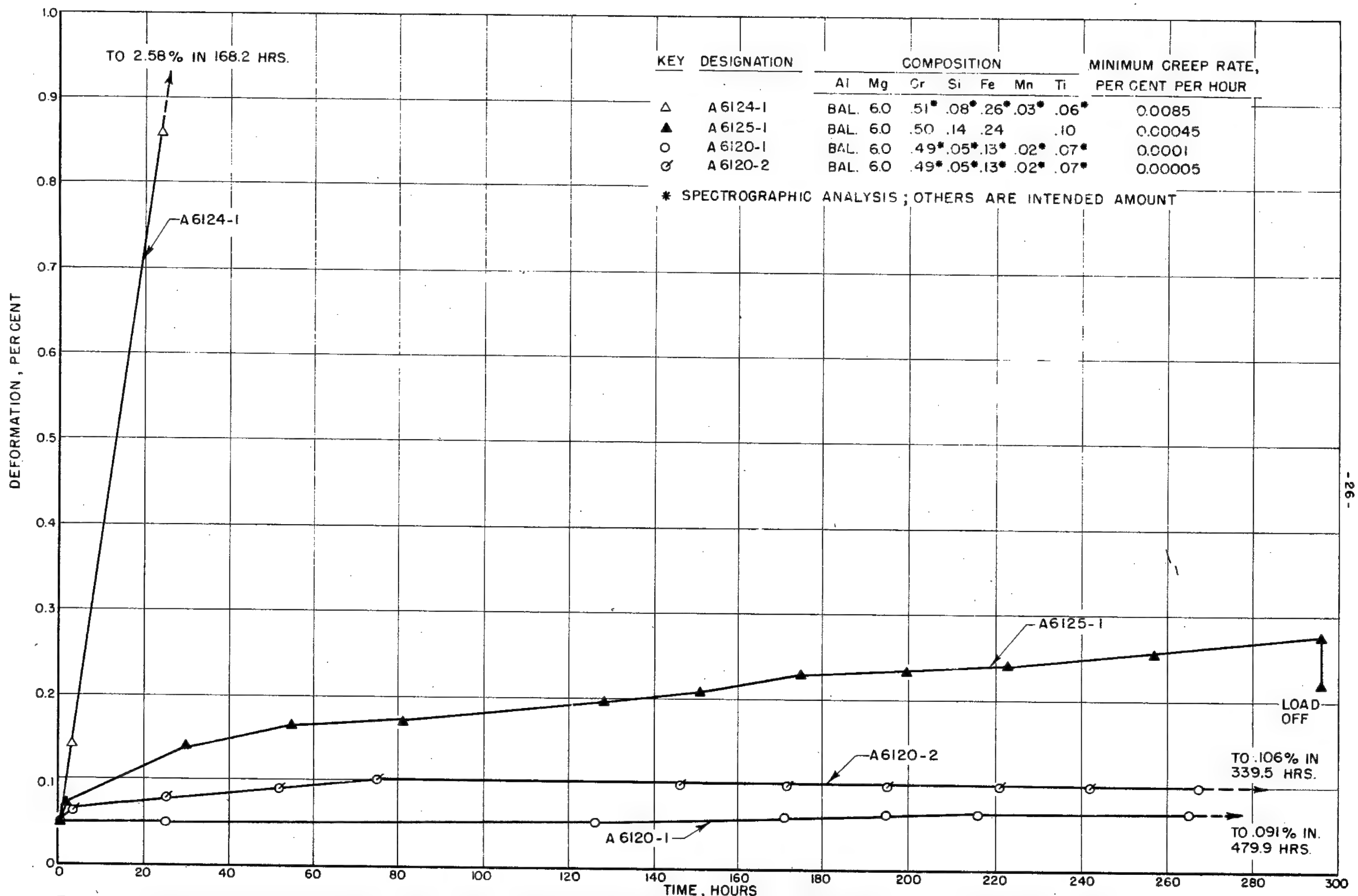

FIGURE 4. TIME-DEFORMATION CURVES OF THREE STABILIZED EXPERIMENTAL ALUMINUM ALLOYS CONTAINING VARIOUS AMOUNTS OF IMPURITIES. MATERIAL TESTED IN FORM OF 0.030-INCH ROLLED SHEET AT 600°F., 2000 P.S.I. LOAD

0-16202

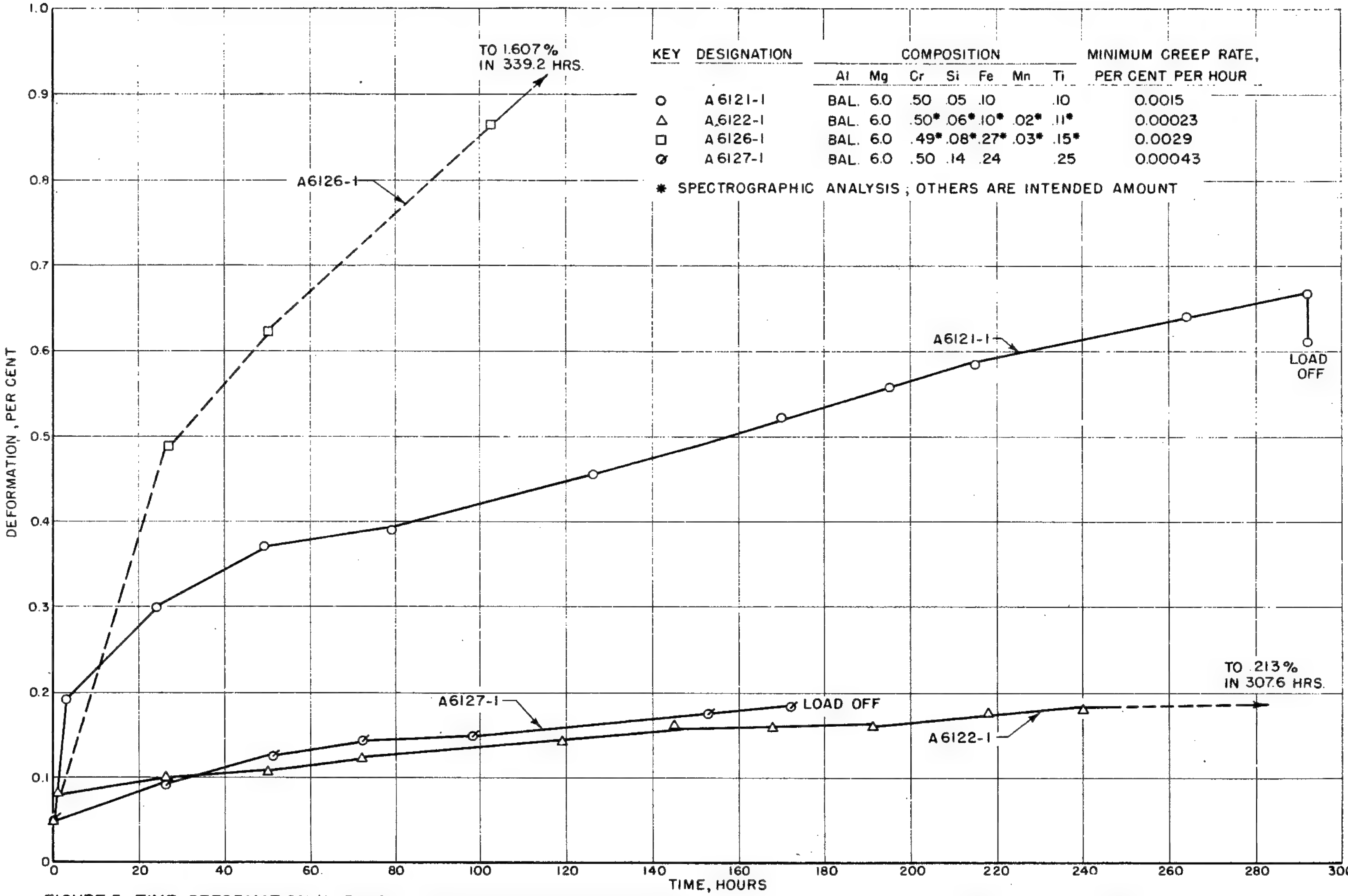

FIGURE 5. TIME-DEFORMATION CURVES OF FOUR STABILIZED EXPERIMENTAL ALUMINUM ALLOYS TESTED IN THE FORM OF 0.030-INCH ROLLED SHEET AT 600°F., 2000 P.S.I. LOAD

0-16203

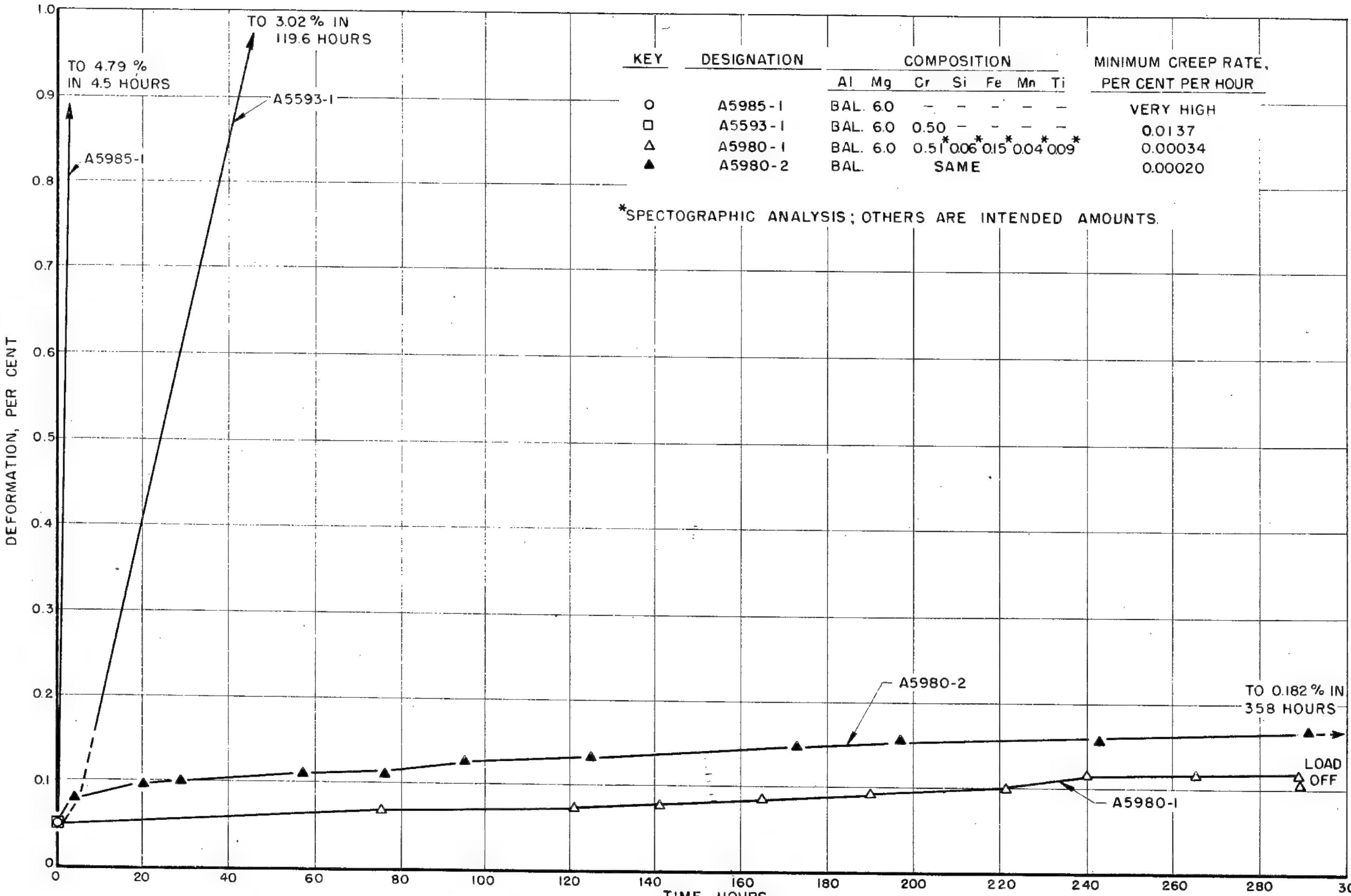

FIGURE 6. THE EFFECT OF COMPOSITION ON THE CREEP PROPERTIES OF THREE EXPERIMENTAL ALUMINUM ALLOYS, MATERIAL TESTED IN FORM OF 0.030-INCH ROLLED SHEET AT 600 °F., 2000 P.S.I. LOAD.

0-16204

Figure 1 shows very clearly that, after the alloys have been stabilized 24 hours at 650°F., the room-temperature tensile properties of the experimental alloy are appreciably superior to those of the 24S composition.

Figure 2 shows the tensile and creep properties of the same five alloys at 600°F. After stabilization prior to test, the experimental alloy has the highest tensile properties at 600°F. The creep resistance of the 6 per cent magnesium binary is very poor, whereas the experimental alloy has a creep resistance about equivalent to that of 24S-T3 with or without prior stabilization.

Typical time-deformation curves are shown for the more interesting compositions in Figures 3, 4, and 5. Figure 3 illustrates a comparison of the time-deformation curves of 24S-T3, 24S stabilized, and three experimental alloys of optimum composition. The two time-deformation curves for Heats A6120 on Figure 4, A6122 on Figure 5, and A5980 on Figure 6 are also representative time-deformation curves of the experimental alloy of optimum composition. It may be concluded from these curves that the resistance of the experimental alloy of optimum composition to creep is of the same order of magnitude as that of 24S.

It should be noted in Table IV that the creep resistance of the 6 per cent magnesium alloys containing chromium and titanium is sensitive to unknown factors. In this respect, it will be noted that a high creep rate was obtained on one specimen of Heat A6124, and a low creep rate obtained on a similar specimen from the same heat. Likewise, Heat A6025, containing 6 per cent magnesium, 0.50 per cent chromium, 0.25 per cent titanium, has a high creep rate under a 2000 p.s.i. load at 600°F. In this instance, however, the poor resistance to creep may be caused by the high

titanium content.

Figures 4 and 5 show some, though inconclusive, evidence that, when high iron occurs in the experimental alloy of optimum composition, the creep resistance is less satisfactory than when the iron content is low.

Figure 6 graphically illustrates the profound effect produced on the creep rate when 0.5 per cent chromium and approximately 0.10 per cent titanium are added to the 6 per cent magnesium alloys.

Conclusions

An investigation was undertaken to improve the properties of wrought aluminum-6 per cent magnesium alloys at 600°F. Although the 6 per cent magnesium binary alloy has very poor resistance to creep, it has been found that the addition of 0.5 per cent chromium and approximately 0.10 per cent titanium produces an alloy which, after stabilization at 600°F. prior to test, has higher tensile properties at room temperature and at 600°F. than 24S. Its resistance to creep at 600°F.-2500 p.s.i. load is about equivalent to that of 24S aluminum alloy. In addition, the aluminum-6 per cent magnesium 0.5 per cent chromium, 0.10 per cent titanium alloy has low density and probably good resistance to corrosion in ordinary environments.

References

1. Aluminum and Its Alloys; Alcoa Handbook, 1944.

2. Grube, K., and L. W. Eastwood: Magnesium-Cerium Casting Alloys for Elevated-Temperature Service; ASTM, 1950.

3. Craighead, C. M., L. W. Eastwood, and C. H. Lorig: Effects of Temperature on the Properties of Aluminum Alloys; RAND Report, April, 1949.

4. Eastwood, L. W., Webster Hodge, and C. H. Lorig: Aluminum-6 Per Cent Magnesium Casting Alloys for Elevated-Temperature Service; ASTM, 1950.

SECTION II.

CORROSION RESISTANCE OF ALUMINUM-BASE ALLOYS IN WATER AT 212-600°F. *

This phase of the project was conducted along with the development of alloys having better strength characteristics at elevated temperatures, as described in the preceding section of this report.

Since the anticipated service of such alloys included prolonged exposure to water at temperatures ranging from 180 to 600°F., tests were run at temperatures as high as 600°F.

At the present time, 2S (99.2%Al) and 72S (1%Zn with a high-purity Al base) are used in applications in which river water attains a temperature as high as about 180°F. The general aim of this part of the investigation, therefore, was to make certain that the increased load-carrying capacity was not attained by a sacrifice in resistance to corrosion, particularly as compared with 2S and 72S. It was also desired that a thermal neutron cross-section value be maintained not appreciably greater than that of aluminum.

The corrosion tests were run in double-distilled water. Those conducted at 212°F. were made in an Erlenmeyer flask, using reflux condensers. The specimens were supported on glass holders. The tests conducted at temperatures higher than 212°F. were carried out in stainless steel autoclaves. The aluminum alloy specimen was fastened to a strip of mica by means of a hook made of the same material as the specimen being tested. The upper end of the mica was attached to the stainless steel holder by means of a Chromel-A wire. The temperature of the autoclave was maintained by means of

* The corrosion tests described in this section were conducted by F. W. Fink and W. E. Berry of the Battelle staff.

Foxboro controllers.

The results of the corrosion tests are listed in Table V. The data on the commercial compositions are listed in the first part of the table. The balance of the table contains the corrosion data on experimental compositions. This table contains data on the composition of the material, the form of the specimen, the heat treatment applied, the temperature, pressure, and duration of the test, the original weight of the specimen, the final weight, the weight increase, and the calculated penetration in inches per year. In many instances, the corrosion rate was too rapid to permit significant values on gain in weight or rates of penetration.

Commercial Alloys

The compositions of the commercial alloys tested are listed in Table VI. Alloys 2S, 72S, and 24S were corrosion tested at 212, 300, 350, 450, and 600°F. The commercial alloys were tested at 600°F. only. From these data, it may be concluded that none of the commercial or experimental alloys have adequate resistance to corrosion in water at temperatures of 600°F. High-purity aluminum, 2S, 52S, 61S, 72S, 75S-T Alclad, and R317 all had very poor resistance to corrosion, whereas the copper-containing alloys, 24S and 17S, and the manganese-containing alloy, 3S, had better resistance to corrosio in water at 600°F. also.

These data on the commercial alloys indicate that service temperatures lower than 600°F. would be very necessary. The corrosion rate increases rapidly as the temperature of test increases. In all probability, temperatures appreciably above 212°F. would not be permissible if a long service life were required.

TABLE V. RESULTS OF CORROSION TESTS OF ALUMINUM ALLOYS MADE IN WATER AT VARIOUS TEMPERATURES AND PRESSURES

Alloy Number	Intended Composition, %, Balance Aluminum	Form of Test Specimen	Heat Treatment(1)	Test Temp., °F.	Pressure, p.s.i.	Hours on Test	Original Weight, Grams	Final Weight, Grams	Weight Gain, Grams	Calculated Penetration, In./Year(2)	Remarks
					Section 1. Commercial Alloys						
A5582	2S (99.5% Al)	0.030-in. sheet	HTS(a)	212	Atmos.	1000	5.3486	5.3626	0.0140	0.000354	30-50 black spots; each spot has a pit under it.
		0.030-in. sheet	HTS(a)	300	50	48			0.0020	0.0062	Thin coating, good metallic luster.
									0.0020	0.0062	Thin coating, good metallic luster.
		0.030-in. sheet	HTS(a)	350	120	48	0.9134	0.9170	0.0036	0.0112	Light gray oxide, some metallic luster.
							0.9062	0.9096	0.0034	0.0107	Light gray oxide, some metallic luster.
		0.030-in. sheet	HTS(a)	450	420	48			0.0078	0.024	Medium gray coating.
									0.0079	0.024	Medium grey coating.
	99.95% Al			600	1500	14	2.567	-	-	-	Samples disintegrated forming a white crystalline powder.
							2.433	-	-	-	
Commercial source	2S			600	1500	4					Samples disintegrated.
	3S	0.032-in. sheet	H14	600	1500	48	0.9210	0.9449	0.0239	-	Smooth gray oxide coating.
							0.9408	0.9641	0.0233	-	
	17S	3/16-in. dia. rod	T4	600	1500	48	1.5116	1.5191	0.0083	0.043	Light gray oxide coating.
							1.4911	1.4988	0.0077	0.040	Light gray oxide coating.
	24S	0.030-in. sheet	T3	212		1000	5.3322	5.3464	0.0142	0.000400	Thousands of tiny black spots, too small at 30 diameters magnification to find pits.
		0.030-in. sheet	T3	300	50	48			0.0018	0.0056	Thin coating, very good metallic luster.
									0.0020	0.0062	Thin coating, very good metallic luster.
		0.030-in. sheet	T3	350	120	48			0.0033	0.0103	Gray oxide, some metallic luster.
									0.0035	0.0113	Gray oxide, some metallic luster.
		0.030-in. sheet	T3	450	420	48	0.8892	0.8947	0.0055	0.018	Streaked surface with some metallic luster.
							0.8887	0.8940	0.0053	0.017	Streaked surface with some metallic luster.
		0.030-in. sheet	T3	550	1045	96	0.8544	0.8705	0.0161	0.03	Brown surface with oxide streak.
							0.8938	0.9096	0.0158	0.02	Brown surface with oxide streak.
		0.030-in. sheet	T3	600	1500	48	0.8080	0.8196	0.0116	0.043	Smooth dark oxide coating.
							0.8537	0.8662	0.0125	0.040	Smooth dark oxide coating.
A5876	4.6Cu,0.6Mn,1.5Mg 99.5Al balance	0.030-in. sheet	HTS(c)	350	120	48			0.0035	0.0104	Dark gray coating.
									0.0036	0.0107	Dark gray coating.
		0.030-in. sheet	HTS(c)	450	420	48	0.7445	0.7518	0.0073	0.02	Dark gray streaked surface.
							0.7569	0.7645	0.0076	0.03	Dark gray streaked surface.
		0.030-in. sheet	HTS(c)	550	1045	96	0.7418	0.7603	0.0185	0.03	Brown surface with oxide streaks.
							0.7484	0.7668	0.0184	0.03	Brown surface with oxide streaks.
		0.030-in. sheet	HTS(c)	600	1500	102	0.7288	0.7475	0.0187	0.03	Brown surface with oxide streaks.
							0.7070	0.7230	0.0160	0.03	Brown surface with oxide streaks.

TABLE V. (Continued)

Alloy Number	Intended Composition, %, Balance Aluminum	Form of Test Specimen	Heat Treat-ment(1)	Test Temp., °F.	Pressure, p.s.i.	Hours on Test	Original Weight, Grams	Final Weight, Grams	Weight Gain, Grams	Calculated Penetration, In./Year(2)	Remarks
A5377	4.6Cu,0.6Mn,1.5Mg, 99.3Al balance	0.030-in. sheet	HTS(c)	350	120	48	0.8958	0.8992	0.0034	0.0109	Dark gray coating.
							0.9014	0.9050	0.0036	0.0118	Dark gray coating.
		0.030-in. sheet	HTS(c)	450	420	48	0.8843	0.8918	0.0075	0.02	Dark gray streaked surface.
							0.8951	0.9032	0.0081	0.03	Dark gray streaked surface.
		0.030-in. sheet	HTS(c)	550	1045	96	0.8882	0.9074	0.0192	0.03	Brown surface with oxide streaks.
							0.8896	0.9084	0.0188	0.03	Brown surface with oxide streaks.
		0.030-in. sheet	HTS(c)	600	1500	96	0.8522	0.8718	0.0196	0.04	Brown surface with oxide streaks.
							0.8690	0.8886	0.0196	0.04	Brown surface with oxide streaks.
Commercial source	24S-T Alclad	0.032-in. sheet		600	1500	48	0.9086	0.9301	0.0215		Smooth gray coating.
							0.8685	0.9345	0.0660		Smooth gray coating.
	52S	0.040-in. sheet	H34	600	1500	48	1.0910	1.2074	0.1164	0.430	Dimensions increased, samples began to
							1.0906	1.2100	0.1194	0.440	crack on edges.
	61S	0.040-in. sheet	T6	600	1500	16	-	-	-	-	Blistered edges split and began to break off.
A5583	72S	0.030-in. sheet	HTS(a)	212	Atmos.	1000	5.6384	5.6538	0.0154	0.000383	About 40 rust colored specks on both faces of sample with pits underneath.
		0.030-in. sheet	HTS(a)	300	50	48			0.0020	0.0063	Thin coating of oxide, good metallic luster.
									0.0020	0.0063	Thin coating of oxide, good metallic luster.
		0.030-in. sheet	HTS(a)	350	120	48	0.8508	0.8539	0.0031	0.0109	Light gray oxide, some metallic luster.
							0.9514	0.9547	0.0033	0.0102	Light gray oxide, some metallic luster.
		0.030-in. sheet	HTS(a)	450	420	48			0.0070	0.022	Medium gray coating.
									0.0071	0.022	Medium gray coating.
		0.030-in. sheet	HTS(a)	600	1500	24	0.7895	0.8001	0.0106		
							0.8257	0.8378	0.0121		
Commercial source	75S-T Alclad	0.040-in. sheet		600	1500	48	1.1016	1.3172	0.2156		Sample blistered. Dark brown on edges.
							1.1261	1.3390	0.2129		Cross section shows very little metallic aluminum remaining.
	R-303	0.032-in. sheet		600	1500	48	1.1423	1.1628	0.020		Dark gray oxide. Streaked in direction of
							1.1455	1.1661	0.021		abrading and rolling.
	R-317	7/32-in.-dia. rod		600	1500	48	2.1321	2.9526	0.8205	-	Samples swelled and cracked, brownish color.
							2.0046	2.7900	0.7854	-	Samples swelled and cracked, brownish color.
					Section 2. Experimental Binary Alloys						
A5584	6.0Mg	0.030-in. sheet	HTS(a)	600	1500	24					Samples disintegrated.
A5592	6.0Mg,0.35Cr	0.030-in. sheet	HTS(a)	600	1500	145	0.865				Samples began to fall apart.
							0.899				

TABLE V. (Continued)

Alloy Number	Intended Composition, %, Balance Aluminum	Form of Test Specimen	Heat Treat-ment(1)	Test Temp., °F.	Pressure, p.s.i.	Hours on Test	Original Weight, Grams	Final Weight, Grams	Weight Gain, Grams	Calculated Penetration, In./Year(2)	Remarks
A5851	6.0Mg,6.0Zn	0.030-in. sheet	S	600	1500	2					Samples disintegrated.
A5852	6.0Mg,6.0Cd	0.030-in. sheet	S	600	1500	2					Samples disintegrated.
A5853	6.0Mg,5.0Si	0.030-in. sheet	S	600	1500	9-1/2					Some oxide, edges splitting.
A5854	6.0Mg,2.0Sn	0.030-in. sheet	S	600	1500	2					Samples disintegrated.
A5855	6.0Mg,2.0Pb	0.030-in. sheet	S	600	1500	2					Samples enlarged approximately 1-1/2 times.
A5856	6.0Mg,2.0Sb	0.030-in. sheet	S	600	1500	2					Samples enlarged approximately 1-1/4 times.
A5857	6.0Mg,2.0Bi	0.030-in. sheet	S	600	1500	2					Samples disintegrated.
A5858	6.0Mg,2.0Ni	0.030-in. sheet	S	600	1500	98	0.8868	0.9061	0.0193	0.03	Samples dark gray with vertical oxide streaks.
							0.8666	0.8858	0.0192	0.03	
A5860	6.0Mg,0.5Ti	0.030-in. sheet	S	600	1500	6					Checked surfaces, edges split and swelled.
A5861	6.0Mg,0.5Cr	0.030-in. sheet	S	600	1500	4-1/2					Edges cracked and swelled, surface cracked and brittle.
A5862	6.0Mg,2.0Mn	0.030-in. sheet	S	600	1500	1-1/2					Surface cracked and warped, edges split.
A5863	6.0Mg,4.0Cu	0.030-in. sheet	HTS(b)	600	1500	93	0.8642	0.8791	0.0149	0.03	Brown surface with white oxide streaks.
							0.8812	0.8967	0.0155	0.03	Brown surface with white oxide streaks.
A5864	6.0Mg,2.0Fe	0.030-in. sheet	S	600	1500	93	0.8348	1.4138	0.5790		Slightly warped, cracking along edges.
							0.8398	1.4228	0.5830		Slightly warped, cracking along edges.
					Section 3. Complex Experimental Alloys						
A5873	4.5Cu,1.5Mg	0.030-in. sheet	HTS(c)	350	120	48			0.0034	0.0107	Gray oxide, some metallic luster.
									0.0034	0.0109	Gray oxide, some metallic luster.
		0.030-in. sheet	HTS(c)	450	420	48	0.9014	0.9090	0.0076	0.03	Dark gray streaked surface.
							0.9355	0.9433	0.0078	0.03	Dark gray streaked surface.
		0.030-in. sheet	HTS	550	1045	96	0.9244	0.9480	0.0236	0.04	Oxide coating, dark red deposit.
							0.9142	0.9341	0.0199	0.03	Oxide coating, dark red deposit.
		0.030-in. sheet	HTS	600	1500	102	0.8776	0.8908	0.0132	0.02	Brown surface with oxide splitting.
							0.8946	0.9075	0.0129	0.02	Brown surface with oxide splitting.
A5874	2.5Cu,3.5Mg	0.030-in. sheet	S	600	1500	102	0.8414	1.2380	0.3966		Samples slightly swollen, edges splitting.
							0.8450	1.2505	0.4055		Samples slightly swollen, edges splitting.

TABLE V. (Continued)

Alloy Number	Intended Composition, %, Balance Aluminum	Form of Test Specimen	Heat Treat-ment(1)	Test Temp., °F.	Pressure, p.s.i.	Hours on Test	Original Weight, Grams	Final Weight, Grams	Weight Gain, Grams	Calculated Penetration, In./Year(2)	Remarks
A5875	1.0Cu,5.0Mg	0.030-in. sheet	S	600	1500	57	0.8080	1.3366	0.5286		Samples slightly swollen, edges splitting.
							0.8094	1.3038	0.4944		Samples slightly swollen, edges splitting.
A5932	6.0Mg,0.16Be	0.030-in. sheet	HTS(a)	350	120	48			0.0060	0.0186	Light gray oxide.
									0.0062	0.0198	Light gray oxide.
		0.030-in. sheet	HTS(a)	450	420	48	0.3604				Sample began to disintegrate.
							0.3619				Sample began to disintegrate.
A5934	6.0Mg,1.6Be	0.030-in. sheet	HTS(a)	350	120	48			0.0046	0.0147	Light gray oxide.
									0.0044	0.0138	Light gray oxide.
		0.030-in. sheet	HTS(a)	450	420	48	0.3219				Samples began to disintegrate.
							0.3203				Samples began to disintegrate.
A5935	1.6Be	0.030-in. sheet	HTS(a)	350	120	48			0.0038	0.0121	Light gray oxide, some metallic luster.
									0.0039	0.0126	Light gray oxide, some metallic luster.
		0.030-in. sheet	HTS(a)	450	420	48	0.8996				Samples began to disintegrate at edges.
							0.8905				Surface has a slight metallic luster.
A5980	6.0Mg,0.50Cr,0.10Ti	0.030-in. sheet	HTS(a)	212	Atmos.	1000	5.2090	5.2198	0.0108	0.000279	Black streaks, blisters at bottom end also etched areas with corrosion product (white).
		0.030-in. sheet	HTS(a)	300	50	48			0.0015	0.0050	Olive green coating.
									0.0017	0.0054	Olive green coating.
		0.030-in. sheet	HTS(a)	350	120	48			0.0034	0.0106	Light gray coating, some metallic luster.
									0.0036	0.0112	Light gray coating, some metallic luster.
		0.030-in. sheet	HTS(a)	450	420	48			0.0533	0.167	Dark gray coating.
									0.0485	0.150	Dark gray coating.
				Section 4. Tests in Water Containing Inhibitors							
				Tests in Water Containing 0.1% Sodium Dichromate							
A5584	6.0Mg	0.030-in. sheet	HTS(a)	600	1500	16					Four samples tested, all disintegrated.
				Tests in Water Containing 1.0% Sodium Dichromate							
A5584	6.0Mg	0.030-in. sheet	HTS(a)	600	1500	16					Four samples tested, all disintegrated.
A5858	2.0Ni	0.030-in. sheet	S	600	1500	16-1/2					Two samples tested, both disintegrated.
A5863	4.0Cu	0.030-in. sheet	HTS(b)	600	1500	16-1/2			-0.0383	0.36	Sample badly pitted.
A5873	4.5Cu,1.5Mg	0.030-in. sheet	HTS(c)	600	1500	16-1/2			-0.0373	0.34	Sample badly pitted.

TABLE V. (Continued)

Alloy Number	Intended Composition, %, Balance Aluminum	Form of Test Specimen	Heat Treatment(1)	Test Temp., °F.	Pressure, p.s.i.	Hours on Test	Original Weight, Grams	Final Weight, Grams	Weight Gain, Grams	Calculated Penetration, In./Year(2)	Remarks
A5876	4.6Cu,0.6Mn,1.5Mg commercial purity	0.030-in. sheet	HTS(c)	600	1500	16-1/2			-0.0122	0.11	Sample badly pitted.
A5877	4.6Cu,0.6Mn,1.5Mg high purity	0.030-in. sheet	HTS(c)	600	1500	16-1/2			-0.0260	0.24	Sample badly pitted.
	24S-T Alclad	0.032-in. sheet		600	1500	16-1/2			-0.0766	0.72	Sample badly pitted.
Tests in Water Containing 1.0% Sodium Silicate - Type "K"											
A5584	6.0Mg	0.030-in. sheet	HTS(a)	600	1500	4					Four samples tested, all disintegrated.
	24S-T Alclad	0.032-in. sheet		600	1500	48					Three samples tested. Uniform oxide coating, some nodules on surface. Edges attacked severely. Metallographic examination showed "Alclad" completely converted to oxide. No noticeable attack on core where "Alclad" continuous. No final weight taken.
	24S	0.030-in. sheet	T3	600	1500	24	0.8840 0.8550 0.8780 0.8894	0.8716 0.8263 0.8477 0.8617	-0.0124 -0.0287 -0.0303 -0.0277		Samples badly pitted and severely attacked.
Tests in Water Containing 0.01% Sb_2O_3											
A5876	4.6Cu,0.6Mn,1.5Mg	0.030-in. sheet	HTS(c)	600	1500	111	0.7360 0.7170	0.7702 0.7468	0.0342 0.0298	0.05 0.04	Dark gray surface. pH start - 6.2; pH end - 8.1.
Tests in Water Containing 1.0% Arsenic (As_2O_5)											
A5876	4.6Cu,0.6Mn,1.5Mg	0.030-in. sheet	HTS(c)	600	1500	48	0.7416 0.7438	0.7404 0.7418	-0.0012 -0.0016		Smooth gray surface. pH start - 1.6; pH end - 3.2.
Section 5.											
Samples Chemically Treated in Boiling 2% Na_2CO_3, 0.5% $K_2Cr_2O_7$ Solution for 10 Minutes, Then 10 Minutes in Boiling 0.5% $K_2Cr_2O_7$, Then Subjected to Corrosion Testing in Water at 600°F.											
A5583	72S	0.030-in. sheet	HTS(a)	600	1500	26-1/2	0.8442 0.9060	0.9276 0.9677	0.0834 0.0617	0.53 0.36	Dark gray surface with numerous small raised spots.

TABLE V. (Continued)

Alloy Number	Intended Composition, %, Balance Aluminum	Form of Test Specimen	Heat Treatment(1)	Test Temp., °F.	Pressure, p.s.i.	Hours on Test	Original Weight, Grams	Final Weight, Grams	Weight Gain, Grams	Calculated Penetration, In./Year(2)	Remarks
						Section 6. (600°F.-1500 p.s.i.)					
			Samples anodized as follows: 1. 15-second dip in 5% HF by volume. 2. Rinsed in tap water. 3. 30 minutes in 15% H_2SO_4 at 75°F. (max.) using 12 amp./sq.ft. 4. 30 minutes in boiling water (sealing treatment).								
A5582	2S		HTS	Samples disintegrated within 15 hours of test.							
A5583	72S		HTS								
A5584	6Mg		HTS								
5598-7	93.5Al,6.0Mg,0.50Cr	1 hour at 810°F. to produce oxide film					0.8350				All samples disintegrated in less than 16 hours at 600°F. distilled water.
-8							0.8730				
-9		2 hours at 810°F. to produce oxide film					0.8574				
-10							0.8476				
-11		3 hours at 810°F. to produce oxide film					0.8464				
-12							0.8392				

(1) Heat treatment

S - Stabilized 24 hours at 650°F.
HTS(a) - Solution heat treated at 810°F., quenched in cold water, and stabilized 24 hours at 650°F.
HTS(b) - Solution heat treated at 960°F. for 20 minutes, quenched in cold water, and stabilized 24 hours at 650°F.
HTS(c) - Solution heat treated at 925°F. for 20 minutes, quenched in cold water, and stabilized 24 hours at 650°F.
H-14 - Commercial designation - in the 1/2 hard condition.
T-3 - Commercial designation - solution heat treated at 920°F. and then cold worked.
T-4 - Commercial designation - solution heat treated at 940°F. with no further treatment.
T-6 - Commercial designation - solution heat treated at 970°F. and then aged at 320°F. for 16-20 hours.
H-34 - Commercial designation - cold worked and then stabilized.

(2) The penetration was calculated from the weight-gain data. The calculations were made only on those samples which possessed an adhering scale or oxide. If any significant "fluffing" off of the scale occurred or if the sample disintegrated, no final weight measurement was made.

TABLE VI. CHEMICAL-COMPOSITION LIMITS FOR COMMERCIAL WROUGHT ALUMINUM ALLOYS USED IN CORROSION TESTS*

Alloy	Cu	Si	Fe	Mn	Mg	Zn	Cr	Ni	Ti	Other Elements Each	Other Elements Total
2S(1)	0.20	(2)	(2)	0.05	-	0.10	-	-	-	0.05	0.15
3S	0.20	0.60	0.70	1.0-1.5	-	0.10	-	-	-	0.05	0.15
17S	3.5-4.5	0.80	1.00	0.4-1.0	0.2-0.8	0.10	0.10	-	-	0.05	0.15
24S	3.8-4.9	0.50	0.50	0.3-0.9	1.2-1.8	0.10	0.10	-	-	0.05	0.15
52S	0.10	(3)	(3)	0.10	2.2-2.8	0.10	0.15-0.35	-	-	0.05	0.15
61S	0.15-0.40	0.4-0.8	0.70	0.15	0.8-1.2	0.20	0.15-0.35	-	0.15	0.05	0.15
72S	0.10	(4)	(4)	0.10	-	0.75-1.25	-	-	-	0.05	0.15
75S	1.2-2.0	0.5	0.70	0.30	2.1-2.9	5.1-6.1	0.15-0.40	-	0.20	0.05	0.15
R303(5)	1.3	-	-	-	2.5	6.5	0.25	0.10	-	-	-
R317(6)	3.5-4.5	1.0	1.0	0.40-1.0	0.20-0.80	0.10	0.25	-	-	0.05(6)	0.15(6)

* Composition in per cent; maximum, unless shown as a range, balance aluminum.
(1) Minimum aluminum content - 99%.
(2) Iron plus silicon - 1% maximum.
(3) Iron plus silicon - 0.45% maximum.
(4) Iron plus silicon - 0.60% maximum.
(5) Nominal composition - limits not given.
(6) Contains 0.3-0.7% each lead and bismuth.

Binary Alloys

Section 2 in Table V contains the corrosion data on binary alloys. These alloys were prepared in the hope that the various additions made to the high-purity aluminum may indicate alloy combinations which would have higher resistance to corrosion than the more complex commercial alloys represented by Section 1 in Table V. It is evident from the data that chromium, zinc, cadmium, silicon, tin, lead, antimony, bismuth, titanium, manganese, or iron added to a 99.8 per cent aluminum base do not produce appreciably better resistance to corrosion than that of the unalloyed aluminum in water at 600°F. Surprisingly enough, however, nickel and copper which usually have an adverse effect in ordinary environments have increased the resistance of the aluminum to corrosion by water at 600°F.

Complex Experimental Alloys

Section 3 in Table V contains the corrosion data on the complex alloys which were prepared primarily to obtain improved load-carrying capacities at elevated temperatures. In general, it was found that none of these complex alloys had adequate resistance to corrosion in water at the higher temperatures.

Section 4 contains data on corrosion rates in water containing various added chemicals which, under some conditions, do or may provide an inhibiting action. The "inhibitors" which were tried were sodium dichromate, sodium silicate, and arsenic oxide. None of these additions appeared to appreciably improve the corrosion resistance of the alloys tested.

Sections 5 and 6 in Table V contain data on the effects of chemical and anodized coatings applied to some of the alloys of greatest interest. Again, however, these chemical coatings described in the table did not effectively decrease the rate of corrosion in water at 600°F.

Conclusions

A considerable variety of commercial and experimental alloys have been subjected to corrosion tests in water at elevated temperatures. None of the alloys tested has appreciable resistance to corrosion in water at 600°F., although those containing approximately 4 per cent copper appear to have the best resistance to corrosion. The corrosion rate in the water decreases rapidly as the temperature is decreased. At 212°F., the resistance to corrosion of 2S, 72S, 24S, and the experimental alloy of optimum composition in the refluxed, boiling, distilled water is very satisfactory. The corrosion data are summarized in Table VII.

The appearance of the alloys did not change during the 1000- to 2000-hour treatment. The blisters observed on one corner of the experimental alloy specimens are probably a result of slight unsoundness in the ingot and are not the result of corrosion.

It is concluded that all four alloys have about equal resistance to corrosion in this particular environment. The load-carrying capacity of these alloys at 212°F. can be approximated by their tensile properties at room temperature, which are as follows:

Alloy	Yield Strength, p.s.i. (0.2% Offset)	Tensile Strength, p.s.i.	Elongation in 2 Inches, %
2S	5,400	12,500	36
72S	6,000	12,300	34
24S-T3	53,600	69,100	17
Experimental	27,000	49,000	22

It is evident that considerably greater load-carrying capacity can be obtained by the use of one of the two high-strength alloys. Of the two high-strength alloys, the experimental alloy has lower density and a lower thermal neutron cross-section value.

(The data from which this report was prepared are recorded in B.M.I. Notebooks No. 4523, pp. 2 to 99, inclusive, and No. 4943, pp. 2 to 31, inclusive.)

TABLE VII. CORROSION RATE ON SMALL SHEET SAMPLES WEIGHING 5 TO 5-1/2 GRAMS (Tests conducted in water at 1 atmosphere pressure, 212°F.)

Alloy	Nominal Composition	Duration of Test, Hrs.	Weight Gain, Grams	Calculated Penetration, In./Yr.	Appearance at the End of 1000 Hrs.
2S	99.5%Al	1000 2000	0.0140 0.0146	0.000354 0.0002	30 to 50 black spots; each spot has a pit beneath it.
24S-T3	4.5%Cu,0.6%Mn, 1.5%Mg	1000 2000	0.0142 0.0145	0.0004 0.0002	Thousands of small black spots; too small at 30-diam. magnification to observe pits.
72S	1%Zn-bal.99.8%Al	1000 2000	0.0154 0.0163	0.000383 0.0002	About 40 rust-colored specks on both faces of the sample with pits underneath.
A5980	6%Mg,0.5%Cr, 0.10%Ti	1000 2000	0.0108 0.0109	0.000279 0.00015	Black streaks, blisters at the lower ends, etched areas with white corrosion product

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